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# Floodplain sediment from a 30-year-recurrence flood in 2005 of the Ping River in northern Thailand

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## Abstract

This paper documents the nature of flood-producing storms and floodplain deposition associated with the 28 September–2 October 2005 30-year-recurrence flood on the Ping River in northern Thailand. The primary purpose of the study is to understand the extent that deposits from summer-monsoon floods can be identified in floodplain stratigraphy. A secondary objective is to document the sedimentation processes/patterns associated with a large contemporary flood event on a medium-sized Asian river. Maximum sediment depths of 15 cm were found on the river levee, within 30 m of the main channel, and at 350 m thickness was 4 cm. Sediment depth generally decreased exponentially with distance away from the main channel. The extent of sediment deposition was about 1 km from the river channel. However, 72% of the sediment was deposited within an oval-shaped area 200–400 m from the main channel and centered on a tributary stream, through which sediment-laden water entered the floodplain, in addition to overtopping the levee of the main channel. Sediment concentration during the flood was estimated at 800–1500 mg L<sup>-1</sup>; and we believe the sediment was delivered by flows of well-mixed flood water occurring over a 1–2 day period. These data suggest that flood-deposited strata related to 30-year recurrence floods is only likely to be preserved in deposits located relatively close to the main river channel where fine sand and clayey coarse silt deposits have thicknesses of at least 5–10 cm. These relatively thick deposits would survive bioturbation, whereas more distal areas with thin clayey silt deposits would not.

## 1 Introduction

Infrequent large floods usually occur in northern Thailand late in the May–October rainy season. Although the May–October rainfall is dominated by storms of moist air moving northeast from the Indian Ocean, large floods are typically associated with tropical depressions moving westward from the South China Sea (Fig. 1). Three flood events

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on the Ping River in August and September, 2005 flooded parts of Chiang Mai city and other floodplain areas within 1 km of the main channel. The first flood (13–16 August) was the result of a heavy monsoon rainstorm associated with a low-pressure trough moving westward across northern Thailand. Chiang Dao District of the Chiang Mai Province reported 200 mm of rain during this period. Flooding and mudslides affected a large area, including Chiang Mai, Chiang Rai, Phayao and Mae Hong Song Provinces (Fig. 2). Peak flow at Chiang Mai reached  $747 \text{ m}^3 \text{ s}^{-1}$  (a stage of 4.90 m) at 18:00 on 14 August. The river flooded again on 21 September reaching a peak flow of  $485 \text{ m}^3 \text{ s}^{-1}$  (3.8 m). This lesser flood was associated with tropical storm Vicente as it weakened to a tropical depression, again traveling westward across Indochina from the South China Sea (20–22 September).

The third and largest flood (29 September–1 October) reached a flow of  $750 \text{ m}^3 \text{ s}^{-1}$  (4.93 m) at the Chiang Mai P1 gage. This event was a result of Typhoon Damrey, which made landfall on Hainan on 25 September and swept westward across the Indochina Peninsula as a tropical storm (Fig. 3). The storm rained 55 mm on 28 September, 43 mm on 29 September, and then 200 mm on 30 September at Chiang Dao (Fig. 4). Rainfall at the Angkhang Meteorological Center near Fang measured 200 mm (Chiang Mai News, 8 October 2006). Flash flooding and mudslides occurred in the same provinces that were hit in August, and additionally in the Lampang and Phrae Provinces (Fig. 2). Scattered small slope failures occurred during the storm along many of the roads. The cities of Chiang Mai and Lampang were partly flooded. The 3-day rainfall in and around Chiang Mai was less than 15 mm, indicating that the main storm passed north of this area. Heavy rainfall apparently occurred along a 100-km wide swath of the west-traveling storm path.

The 28–30 September storm is characteristic of storms producing major floods with greater than 10-year recurrence in northern Thailand. Heavy rainfall occurs along a westerly-travelling storm path after landfall of a South China Sea typhoon. These storms are limited in their north-south extent, and often occur in August and September. The 14 September 1994 flood on the Ping River, for example, was associated

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with the westerward traveling storm from Typhoon Harry. Kidson et al. (2005) indicate that the 12 August 2001 storm produced a 16-year recurrence flood peak on the Mae Chaem River, and the BBC news (2001) reported this storm caused disastrous flooding in Vietnam and in the Petchabun Province of Thailand associated with Typhoon Usagi. Such storms, however, are not restricted to the late summer monsoon. The 21–23 May 2006 storm was a low-pressure system that produced heavy rainfall, disastrous flooding and mudslides in the Dannang Province of Vietnam and the Uttaradit and Sukothai Provinces of northern Thailand (Asian Disaster Preparedness Center, 2006). This weather system occurred 5 days after the eye of Typhoon Chanchu changed its track from NW to NE about 1000 km off the coast of Vietnam, apparently a result of unsettled atmospheric conditions at the onset of the summer monsoon.

Because sediment concentrations during large flows in the Ping River typically exceed  $500 \text{ mg L}^{-1}$  (Royal Irrigation Department, 1995, 1996, 1997), the potential for substantial “silt” deposition during flooding is high – although this phenomenon has never been documented in detail. Most studies of sediment deposition during individual big floods has been on European and North American large rivers that commonly have suspended sediment loads less than  $500 \text{ mg L}^{-1}$  (Asselman and Middelkoop, 1995; Gomez et al., 1995). Understanding sedimentation from infrequent large floods on moderate-sized SE Asian rivers is of interest because sediment concentrations can be quite high. Depositional evidence of these events, however, is often short-lived on account of lush vegetation and frequent cultivation of the floodplain areas. It is intuitive to think that the depth of floodplain sedimentation is related to the duration of the over-bank stage and the concentration of suspended sediment at the time of inundation. In this work we measured the thickness of mud sediment deposited on the floodplain of the Ping River following 29 September 2005 flood event. The purpose of our study was to understand the nature of storms producing 30-year recurrence floods, to investigate phenomena affecting the sedimentation patterns, and to describe the sediment to aid in interpretation of floodplain stratigraphic studies in the area (e.g. Wood et al., 2007).

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2 Study area

The Ping River drains a mountainous area of northern Thailand with steep hills up to elevation 1500 to 2000 m, and valleys at 330 to 500 m (Fig. 3). The Ping River basin is underlain by older Paleozoic gneissic granites, Paleozoic sediments and volcanics, Mesozoic granitic rocks, and Tertiary continental basin-fill sediments (Hess and Koch, 1979; Rhodes et al., 2005). The lowlands are underlain by alluvial fan, terrace, and floodplain deposits (Margane and Tatong, 1999). Upland areas and older terrace and fans have deep weathering profiles of saprolite one to tens of meters thick overlain by red-yellow argillic soil horizons one to several meters thick. Surface soils are dark brown loams up to 25 cm thick. Valley bottoms are mostly clayey silt with gleyed soils in the paddy areas.

It was estimated that 70 per cent of northern Thailand highlands were covered by subtropical forest in 1960. Logging and clearing for agriculture had reduced forest cover to 43% by 1998 (Charupatt, 1998; Thomas et al., 2002). Forested hills are mostly covered by 2nd growth deciduous and evergreen forest with bamboo thickets. Only a few steeper areas have original canopied forests with tall trees (20–30 m high). Many hillsides are partly cleared and have many trails and roads. Cultivated crops included corn and upland rice; flower farms and commercial greenhouse-style agriculture is more prevalent than in the recent past.

The river courses through the Chiang Mai basin, with a floodplain about 3 km wide, extending about 1 to 1.5 km to either side of the river, beyond which are alluvial benches that rise 5 to 10 m above the floodplain. The lowlands consist of fruit orchards, paddy-rice fields and urban areas and villages. The river flows in a single alluvial channel of low sinuosity using terminology of Leopold and Wolman (1957). The channel is 40-to-70-m wide. It is largely a sand-bed river along this reach. Leveed banks are typically 3 to 4 m above the channel bed. Many levees are utilized for narrow one-and-two-lane surfaced roadways. Levees are 0.5 to 1 m above the floodplain. River gradient determined from 1:50 000 maps is 0.0006 m m<sup>-1</sup>.

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The Ban Ko village study area (Figs. 2–5) is located 12 km downstream from the P-1 stream gauge at the Nawarat Bridge in Chiang Mai. Mean annual discharge of the Ping River at P-1 is  $26 \text{ m}^3 \text{ s}^{-1}$ . The Ping River above gauge P-1 has a drainage area of  $6355 \text{ km}^2$  (Fig. 2). Of this drainage area, 1/5 is regulated by the Mae Ngad Dam (active volume of 90 million  $\text{m}^3$ , total volume of 302 million  $\text{m}^3$ ), which has controlled drainage from about  $1300 \text{ km}^2$  since 1977. No major tributaries or diversions exist between Ban Ko and P-1; therefore, this gauge is a good measure of flow to the study area

### 3 Flood hydrographs and flood recurrence

Peak flows on 14 August ( $747 \text{ m}^3 \text{ s}^{-1}$ ) and on 29 September ( $750 \text{ m}^3 \text{ s}^{-1}$ ) were considered 30-year recurrence events based on the 1954–2005 flood-history record (Figs. 5 and 6). The annual flood peak is 370 to  $450 \text{ m}^3 \text{ s}^{-1}$ , and the 10-year event is  $620 \text{ m}^3 \text{ s}^{-1}$  (Fig. 6). The largest flood in recent history occurred in 1952, with an estimated flow in excess of  $830 \text{ m}^3 \text{ s}^{-1}$ . Prior to 1950, little is known of the flood history of the Ping River. A large flood in 1831 is believed to have caused major channel changes and sedimentation over the 13th Century city of Wiang Kum Kam, 6 km upstream from the Ban Ko village study area (Velechovsky et al., 1987; Wood et al., 2004). Kidson et al. (2005) identified paleoflood evidence in the adjacent Mae Chaem River drainage with a peak discharge of  $2479 \text{ m}^3 \text{ s}^{-1}$  which greatly exceeds the 1961 flood of  $980 \text{ m}^3 \text{ s}^{-1}$ , the largest flood of the Mae Chaem record. Their paleoflood work suggests the potential for much larger flood peaks on the Ping River than those which occurred in the record since 1950.

### 4 Measurements

We measured the thickness of mud sediment deposited on the floodplain at Ban Ko where the peak flooding was photographed at 16:00 on 29 September from the window

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of a commercial aircraft (Fig. 7).

Sediment-thickness measurements were made on 2 October, and also on 7 October to cover those areas that were underwater on 2 October. Our method was to slog through the wet mud-mantled fruit orchards and rice fields and measure soft mud thickness with a millimeter ruler at more than 200 locations over a 0.27-km<sup>2</sup> area (Fig. 8a). Locations were determined with hand-held GPS units to a ±7 m precision. Where thickness was questionable, the light-brown mud was scraped away to the darker, firmer, gray mud of the August depositional surface. Sediment thickness was also measured on floors of four elevated bamboo shade huts, where farmers rest in the heat of the day (Fig. 8b). Sediment from the upper part of the water column had settled on these elevated platforms; and therefore, provided information to compare with the sediment thickness on the surrounding ground that received sedimentation from the full water column. In March 2006 an elevation profile was surveyed using a laser level in order to better understand the pattern of flooding (Fig. 9).

## 5 Results

### 5.1 Sediment concentration

Total suspended sediment concentration of 1020 mg L<sup>-1</sup> was determined from one grab sample of the turbulent, muddy, brown floodwaters at Chiang Mai. Sample was taken from 0.2-m deep at the west abutment of Nawarat Bridge near the P-1 gaging station at 16:00 on 30 September. River was in full flood at 740 m<sup>3</sup> s<sup>-1</sup> (4.9 m stage). This value is much higher than any values shown on sediment rating curves (1994–1997) (Fig. 10). Because our 1020 mg L<sup>-1</sup> concentration was taken just after peak flow, it might be low compared with the concentrations on the rising limb of the flood hydrograph. We have only this limited sediment concentration data for the Ping River; however, in monitoring a 75-km<sup>2</sup> tributary watershed, values sometimes exceed 8000 mg L<sup>-1</sup> during large runoff events (Ziegler, unpublished data). Thus, there is potential for relatively high

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concentrations in the Ping. Despite only having one sample, and knowing little about the sediment-concentration hysteresis pattern of typical large flows in the Ping river, we estimate that the floodwater contained between 800 to 1500 mg L<sup>-1</sup> of suspended solids when it inundated the study site at Ban Ko.

5.2 Sediment thickness

Greatest thickness in the Ban Ko study area was 15 cm of silty-fine-sand sediment along the levee on the north side of the Ping River (Site A, Fig. 11). A pocket of thick sediment was located near the tributary channel. Sediment thicker than 8 cm covered 16% of the study area, and extended no more than 250 m from the main channel. Sediment thicker than 4 cm covered 44% of the area and extended no more than 350 m from the main channel. At a distance of 450 m from main channel, sediment thickness diminished to 0.5 cm (Fig. 11). Thickness averaged over the 0.27-km<sup>2</sup> area is 3.3 cm; this equates to a wet sediment volume of roughly 9000 m<sup>3</sup>. Converting the volume of wet sediment ( $\rho_{\text{wet}}=1.6 \text{ g cm}^{-3}$ , water content = 0.60) to dry weight indicates that about 9000 Mg of material was deposited over the 0.27-km<sup>2</sup> area. The average dry sediment deposit is 33 kg m<sup>-2</sup>; however, 72% of this material is bounded by the 2-cm isopach contour, within 200–400 m of the river channel.

Sediment thicknesses were measured on elevated platforms of 4 huts (Fig. 12). These data indicate that the amount of sediment intercepted by the platform, and that which settled to the bottom was roughly proportional to the thickness of the overlying water column. For example, at hut H2 (Fig. 8b) the flood depth was 1.2 m over the ground and 0.55 m over the hut floor (Fig. 12). From these observations we conclude that the suspended sediment concentrations were relatively uniform in the water column from which sediment settled. In other words, the water delivered to the point of sedimentation was well mixed from top to bottom.

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### 5.3 Appearance of sediment layers

Fine sand occurred only on the levee area, within 50 m of the main channel of the Ping River (Fig. 13a). Within 150 m of the main channel is a 3-to-6-cm layer of coarse silt (0.03–0.06 mm) showing indistinct upward fining (Fig. 13b). This coarse silt was overlain by a distinct layer of massive clayey silt in some locations (Fig. 13c). We believe this two-layer stratigraphy occurred in low areas that were fed floodwater at a lesser velocity than the initial surge that bore the coarse silt. At more distant sites the sediment was entirely massive clayey silt (Fig. 13c).

When photographed on 4 November, beneath the light-brown sediment of the September flood was gray clayey silt (Figs. 13b, c, d), which at sites P2 and B is 9-cm thick over a thin leaf layer that was assumed to be the pre-August flood surface. This sediment changed to a gray color within only 2.5 months. The August sediment was submerged by water for at least 1.5 months, whereas the water from the September flood drained within 2–3 weeks. The gray layer shown in Fig. 13c contained mm-scale light-brown streaks of coarser silt. Bioturbation of the flood sediment had already begun at some sites, as was indicated by rust-colored outlines of insect burrows, abundant in the gray sediment layer shown in Fig. 13b. In areas where sediment was less than 1.5 cm thick, the September sediment could not be discerned as a separate layer.

### 5.4 Density and grain-size analysis

Wet density of the mud and grain-sizes were determined for seven samples in the study area (Fig. 14). Density of most wet mud samples varied from 1.6 to 1.7 g cm<sup>-3</sup>; and the water content (water mass/mass of dry solids) ranged from 0.67 to 0.83. Grain size analyses indicate these sediments to be a silt with 20 to 45 per cent clay (Fig. 14). One sediment sample located at point A (Fig. 11) had a density and moisture content of 1.86 g cm<sup>-3</sup> and 0.3, respectively. This was a silty fine sand with 45 per cent fine sand and 17 per cent clay that was deposited on the levee about 15 m from the channel. Collectively the analyses show that grain size diminishes with distance from the

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tributary channel. This pattern in grain size, and particularly the pattern in thickness, suggests that the tributary channel was a primary conveyor of sediment from the Ping River to the floodplain.

## 6 Discussion

### 6.1 Nature and extent of flooding

The flooded Ban Ko study area is shown in the 29 September photograph (Fig. 7). Water delivered to this area flowed over the levee on the main channel of the Ping River, as well as up a low-gradient tributary channel – and then most likely set up a weak current over the floodplain area that exited over the levees (Fig. 11). The estimated flooded area shown in the photograph is about 1 km<sup>2</sup> (Fig. 10). Based on water level stains (Fig. 8a) and the level survey (Fig. 9), the average depth of floodwater in the back-levee area was 1.2 m which is equivalent to a water volume of 1.2 million cubic meters. Because the bed of the tributary channel grades to the low-water main-channel bed, the tributary channel at flood stage could accommodate flow through a cross section 5 m deep and 12 m wide. This particular tributary channel did not have a flood gate, as many channel/canals in the area do. Floodwater overtopping roads did not damage the levees; and no substantial breaches occurred, despite floodwater reaching 0.5 m at some places.

It is useful to consider how the sediment could have been conveyed to the floodplain through the channel of the tributary. Discharge of water flowing at 1.5 m s<sup>-1</sup> velocity through the tributary channel (5-m deep and 12-m wide) would have been 90 m<sup>3</sup> s<sup>-1</sup>. The depth of water over much of the 0.27 km<sup>2</sup> area was 1.0 to 1.4 m deep, which converts to a volume of 1.2 million cubic meters. About 4 h would be needed to deliver 1.2 million cubic meters. If the sediment were delivered by one ingress of water to flood the area to a depth of 1.2 m, we can estimate the thickness that would have been deposited. Consider a column of water 1.2 m (120 cm) deep, and a 1 cm<sup>2</sup> area, bear-

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ing  $1000 \text{ mg L}^{-1}$  of sediment. That sediment, if settled, would have a mass of 0.12 g. Sediment with an average density of  $1.6 \text{ g cm}^{-3}$ , would amount to only 0.75 mm thickness. Because we measured an average of 3.3 cm thickness over the area (Fig. 11), it is clear that the deposited sediment resulted from at least 40 volumes of flood water (3.3 cm ÷ 0.075 cm = 44). The data from the elevated platforms of huts suggest that each water columns from which the sediment was derived was well mixed, and not greatly stratified. Therefore, a flow of water into this area must have occurred on the time scale of 1–2 days, not several hours, to produce the observed sediment thicknesses – and this supports the role of backflow up the small tributary stream as conveying some of the flood water from the Ping River. The greater sedimentation near the tributary channel is similar to that of a crevasse splay, but differs because the channel delivering floodwater to the floodplain was not a breach in the levee, but rather a preexisting tributary channel that graded to the low-water bed of the main channel, and delivered mostly silt rather than sand typical of crevasse splay deposits. While the pattern we found at the Ban Ko study area cannot be applied to the whole Ping River floodplain, it can serve as an indicator for areas that were submerged more than 1 m for similar lengths of time. Figure 7 shows that the southeast side of the river was not significantly flooded, because the levees were higher and there were no major openings in the levee. In addition, sandbags placed along the road held back much of the floodwater. The flooded river was not surveyed from the air over its length at peak flood, so we cannot estimate amount of sediment deposited over the entire Chiang Mai basin. We did observe a similar 1-to-8-cm of sedimentation within the low areas of the Chiang Mai city, and therefore believe these results are a useful indicator of sedimentation in the extensively flooded areas there as well.

## 6.2 Comparison with other flood studies

Floodplain sedimentation is patchy and irregular; and it occurs mostly where channels and unleveed low areas route floodwaters to otherwise leveed areas, and to low ar-

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eas of the floodplain. Our data generally show the exponential decline in sediment thickness away from the main channel (Fig. 11a) that is reported in other studies of flood sediment, and long-term vertical accretion (Bridge, 2003). The overall scale of floodplain sedimentation is less than, but similar to, that of the April–June, 1973 flood on the Mississippi in Louisiana (USA). For that flood, Kesel et al. (1974) found that sediment thickness and texture decreases away from the river: e.g., 400 m from the river, sediment thickness was about 2 cm; however sediment depths of 0.5 to 1.0 cm extended 10 km away from the channel. Peak discharge of the 1973 Mississippi flood was  $42\,500\text{ m}^3\text{ s}^{-1}$ , and large areas were inundated with 4 m of water for 2 months. Suspended sediment concentrations were not reported.

Gomez et al. (1995) found remarkably small sediment thickness ( $<0.4\text{ cm}$ ) on leveed and unleveed floodplain areas from the July–August 1993 flood, which had a peak discharge of  $12\,320\text{ m}^3\text{ s}^{-1}$  on the upper Mississippi River. At Keokuk, Iowa this discharge was about 20% larger than that of the 1973 flood mentioned above. They attribute low sedimentation to relatively low suspended sediment concentrations ( $<500\text{ mg L}^{-1}$ ). However, extensive mud-draped sand deposits up to 30 cm thick are documented out to 6.4 km (4 miles) from the channel, at the levee break at Miller City, Illinois (Jacobson and Oberg, 1997)

Similarly, the September 1999 flood associated with Hurricane Floyd, on the Tar River, North Carolina ( $5654\text{ km}^2$  drainage area), deposited only a thin layer of sediment on the floodplain (Leece et al., 2004). This flood had a peak discharge of  $1999\text{ m}^3\text{ s}^{-1}$  and a duration of almost 30 days. It was considered the  $>500$ -year-recurrence flood; and water depth in some floodplain areas was 3 m. Median thickness of fine sediment was 0.09 cm, and the maximum was 1 cm over the 2–5 km wide floodplain. They estimated maximum suspended sediment concentrations were less than  $465\text{ mg L}^{-1}$ ; and the authors attribute small deposition to low suspended sediment concentrations.

The 2005 flood deposits we found at Ban Ko site along the Ping River are thicker than those described in the literature because of greater suspended sediment concentrations, and also because conveyance of the floodwater was not simply overbank flow.

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Much of the floodwater conveyance to the floodplain at Ban Ko was through a tributary channel; and this allowed thick sediment deposits to occur farther inland than would be expected for only overbank flooding.

7 Conclusions

Two of the three 2005 floods on the Ping River reached peak flows near the estimated 30-year recurrence interval. Duration of these floods was 2 days (14–15 August) and then 3 days (29 September–1 October). Low floodplain areas of the city of Chiang Mai and elsewhere in the Chiang Mai Basin were flooded with water up to 1.5 m deep, extending out to 1 km from the main channel. The significance of the sediment distribution patterns we observed at the Ban Ko flood site is that long-term stratigraphic evidence from floods of this magnitude is only likely to be preserved in deposits within about 100 m of the river channel – either on the levee, in areas where the levee was breached, or locations where tributary channels allow ingress of floodwaters to the floodplain. These deposits are fine sand and clayey coarse silt, have thicknesses of 5–10 cm, and may survive bioturbation by soil fauna and emerging roots. More distal areas with less than 3-cm-thick deposits of clayey silt would probably not survive as discrete layers in the stratigraphy of the floodplain deposits. We observed that such thin deposits were already burrowed by insects 3 months after deposition. Sedimentation by the relatively short-duration floods we studied was greater than that reported from many North American and European examples, largely because the suspended sediment concentration was greater (estimated to be in the range 800–1500 mg L<sup>-1</sup> versus <500 mg L<sup>-1</sup> for the Northern American and European examples). Furthermore, the conveyance of floodwater was not simply overbank flow, but was augmented by inflow of floodwaters through a tributary channel that did not have a flood gate.

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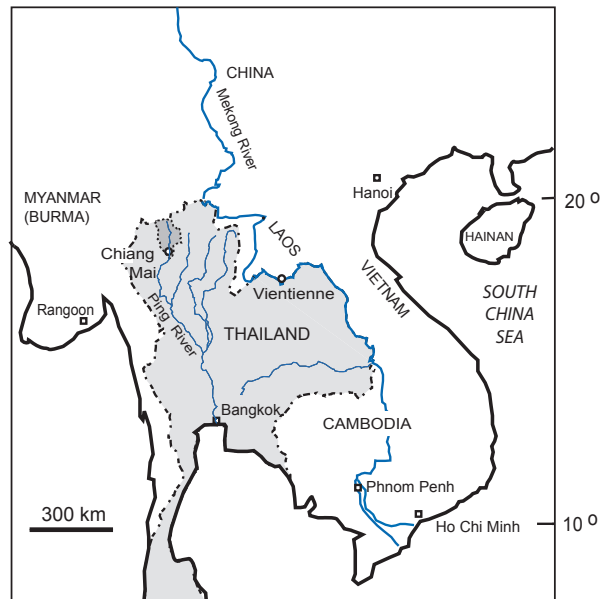
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**Fig. 1.** Location of the Ping River. Dark shaded area is drainage area upstream of Chiang Mai and the study area.

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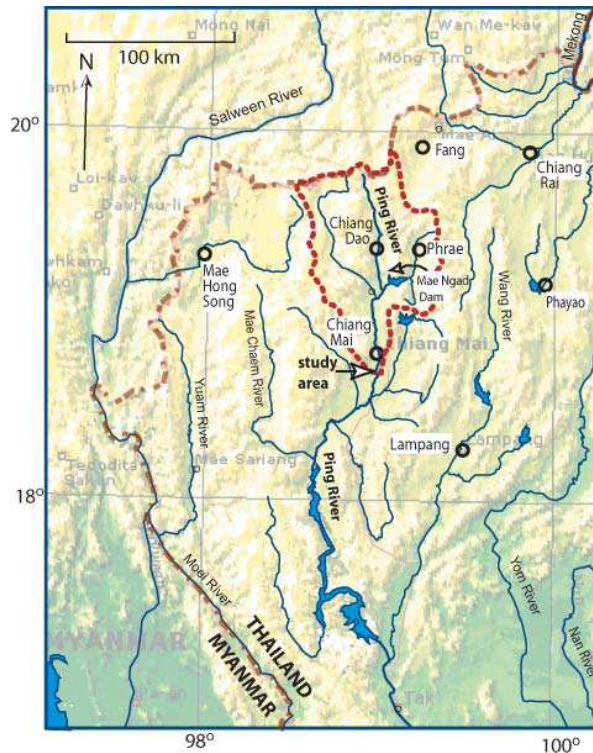
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**Fig. 2.** Outline of the Ping River drainage (dotted line) upstream of the study area showing the location of the dam on the Nam Mae Ngad which regulates flow from 1/5 of the drainage. Labeled cities are those provincial capitols which reported major flooding 12 August–4 October 2005.

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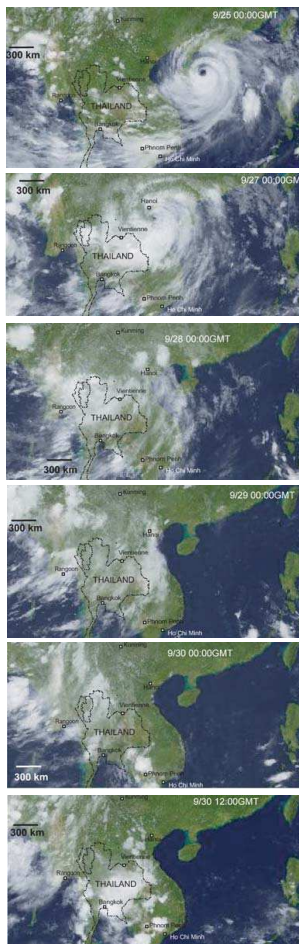
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**Fig. 3.** Satellite images showing the westward traveling tropical storm from Typhoon Damrey, 25–30 September 2005. Ping River drainage basin above Chiang Mai P1 gage outlined with dotted line. From archive of EEL-lab, Kochi University, MTSAT IR IR1 JMA. Thailand local time is 7 h later than GMT.

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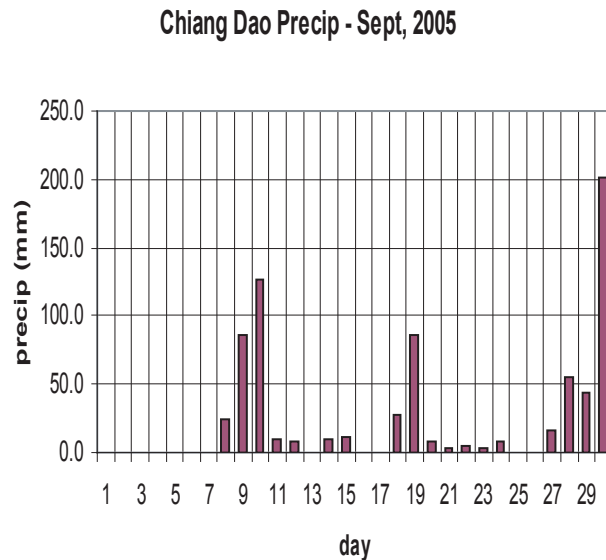
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**Fig. 4.** September 2005 daily precipitation at the Ban Pahng Ma Oh Watershed Research Station, Mae Na Subdistrict, Chiang Dao District. No rain occurred for several weeks after the 30 September storm.

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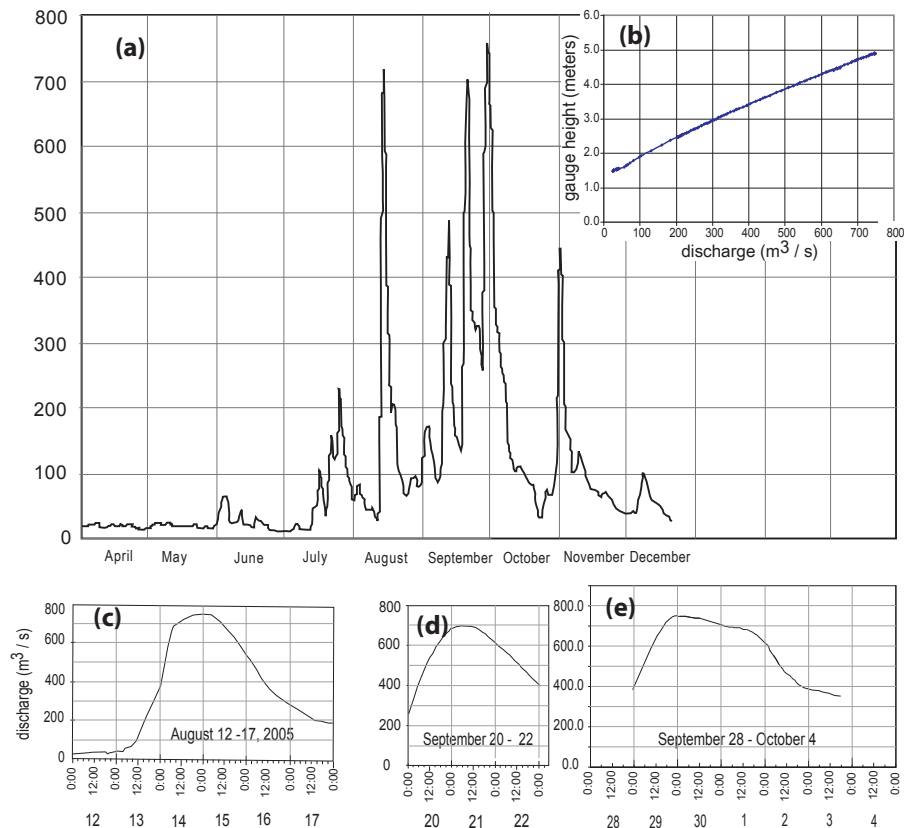
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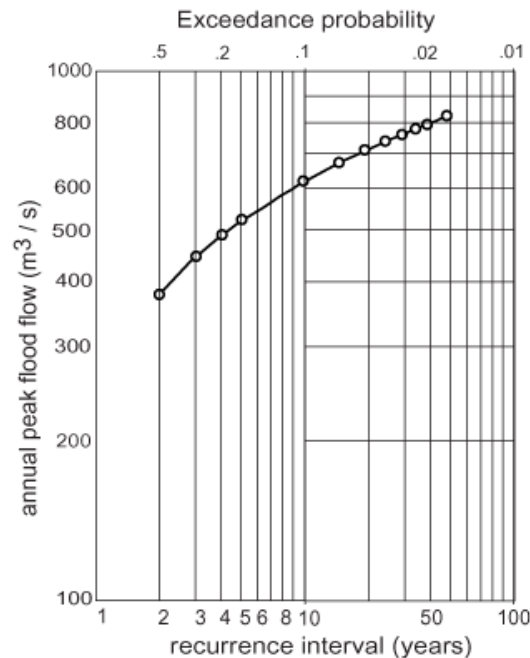
discharge ( $\text{m}^3 / \text{s}$ )



**Fig. 5.** Hydrographs of daily-mean flow readings at the P1 gage at Narawat Bridge in Chiang Mai. **(a)** the mean-daily flow 2005 hydrograph, **(b)** Stage-flow relationship, **(c)** hourly flow – 12–13 August, **(d)** hourly flow – 20–22 September, and **(e)** hourly flow – 29 September–2 October, (Data from Royal Irrigation Department, Hydrology and Water Management Office: internet site: <http://www.hydro-1.net>).

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**Fig. 6.** Flood frequency graph constructed from the 1954 to 2005 record, and including the reported record peak flood flow of 830 m<sup>3</sup>/s of 1952. Graph from an unpublished report of the Hydrology and Water Management Center for the Upper Northern Region of the Royal Irrigation Department.

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**Fig. 7.** Photo from airplane of the flooded area of the Ping River at peak flood flow 16:00, 29 September 2005. View is to the east toward the bridge at Ban Mae Kha. Tributary channel joins the river on the right (downriver) side of photo. Area of mapped sediment thickness (Fig. 5) extends from the white building (left center of photo) to the river.

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**Fig. 8. (a)** high water line on fruit trees. Floodwater depth was 1.3 m. Location is at point B of Fig. 11. View is to the southeast. **(b)** hut located at point H2 on Fig. 11. Five cm of sediment deposited on platform elevated 0.55 m above ground (see Fig. 12). Photos taken on 2 October.

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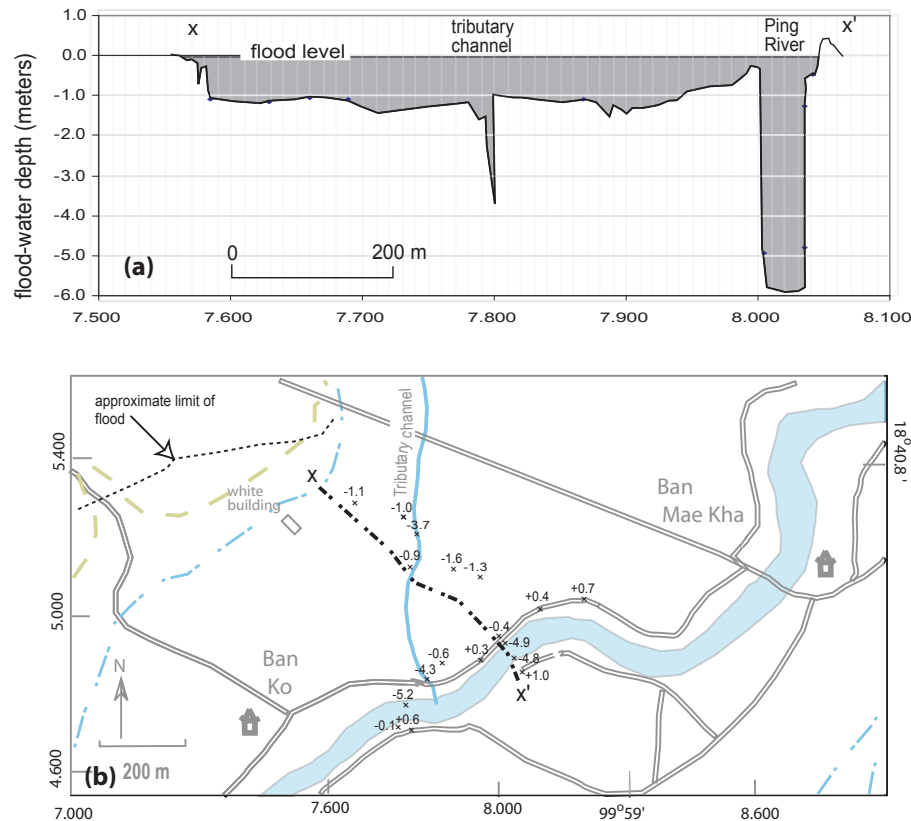
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**Fig. 9. (a)** Map of surveyed ground elevations below maximum flood level. **(b)** elevation profile along line x-x' showing maximum flood level in area of sediment thickness survey.

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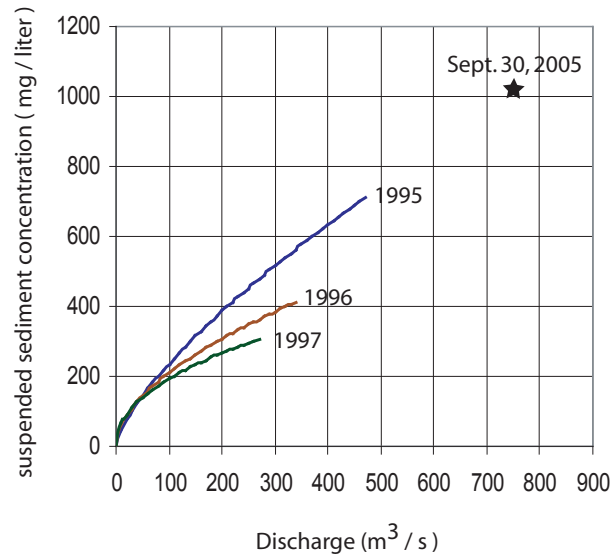
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**Fig. 10.** Suspended sediment concentration (single surface grab sample) measured during flood flow of  $750 \text{ m}^3/\text{s}$  on 30 September 2005 at Narawat Bridge, compared to suspended-sediment rating curves for the Ping River P1 based on sampling by the Royal Irrigation Department in 1994, 1995, 1996, and 1997. In those years peak flows reached 525, 467, 342, and  $270 \text{ m}^3/\text{s}$ , respectively.

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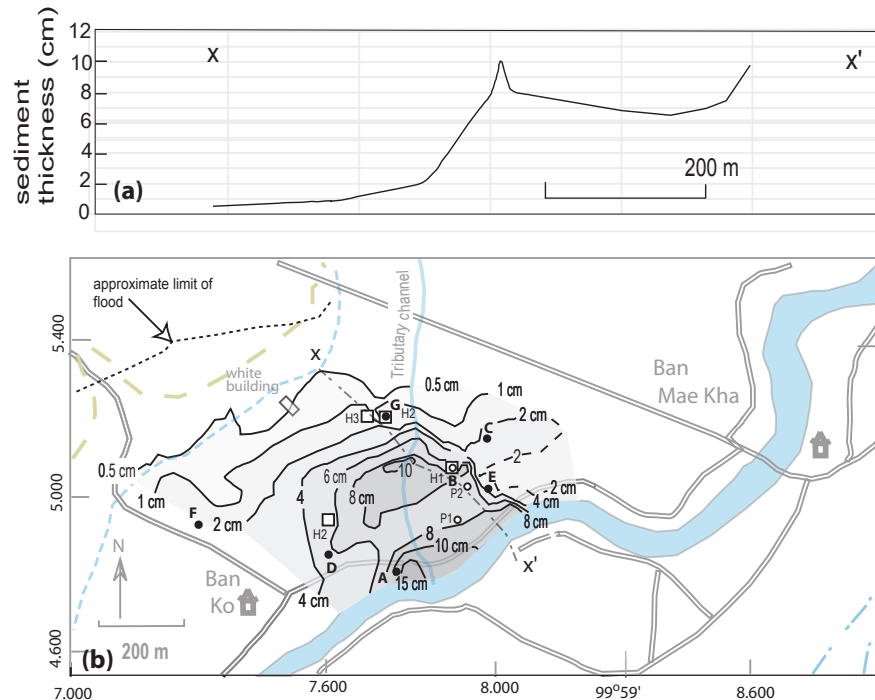
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**Fig. 11. (a)** Profile of wet sediment thickness along line x-x'. **(b)** Isopach map of wet-sediment thickness deposited on floodplain and levee during the 29 September–2 October flood. Points A–G are locations of samples for which grain size analysis are shown in Fig. 14. Points H1–H4 are locations where thicknesses were measured on elevated platforms as well as on the surrounding ground (data shown in Fig. 9). Line x-x' is the line of profiled thickness in Fig. 11a and profiled elevation in Fig. 9b. Photos of sediment are shown in Fig. 13 at locations A, B, P1, and P2.

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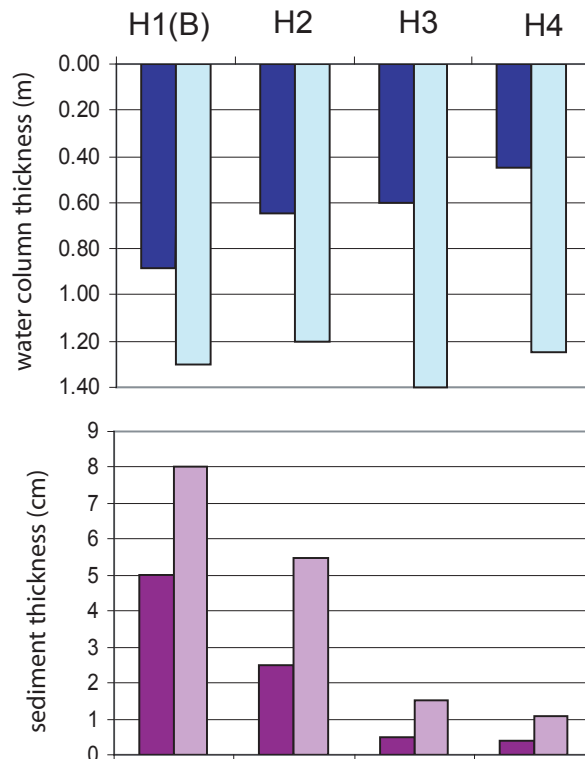
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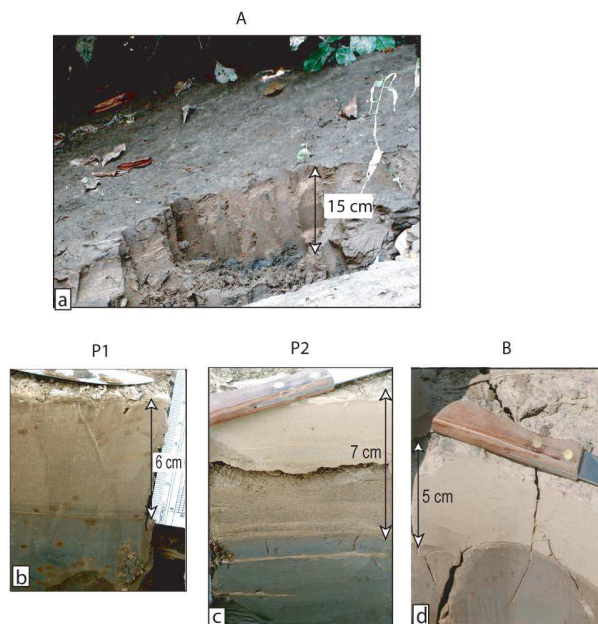
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**Fig. 12.** Upper graph shows thickness of the column of water over elevated platforms (dark pattern) compared to the total depth of water at the site (pale pattern). Sediment thickness deposited on elevated platforms (dark pattern) compared to thickness on the surrounding ground (pale pattern). Locations of H1(B), H2, H3, H4 shown in Fig. 11.

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**Fig. 13.** Photographs of 29 September–2 October sediment at locations P1, P2, B, and A shown in Fig. 5. **(a)** Brown, massive, clayey coarse silt overlying grey clay of the August flood at point, P1, 100 m from river channel. The 6-cm-thick layer shows slight upward fining, and has developed several rust-stained insect burrows when photographed 2 months after deposition. 4 November photo. **(b)** Sediment shows a basal 3.5-cm layer of brown clayey coarse silt overlain by 3.5 cm of pale brown clayey silt that has dried and parted from the layer below. The underlying gray August sediment has light-brown silty streaks. 4 November photo at point P2, 160 m from river channel. **(c)** Massive 5-cm layer of brown clayey silt at site B, 200 m from the river channel. Grain-size analysis shown in Fig. 10. 4 November photo. **(d)** River-channel-facing levee deposit on a 20-degree slope at site A. Deposit is 15 cm of brown silty fine sand (grain-size analysis shown in Fig. 10). 7 October photo.

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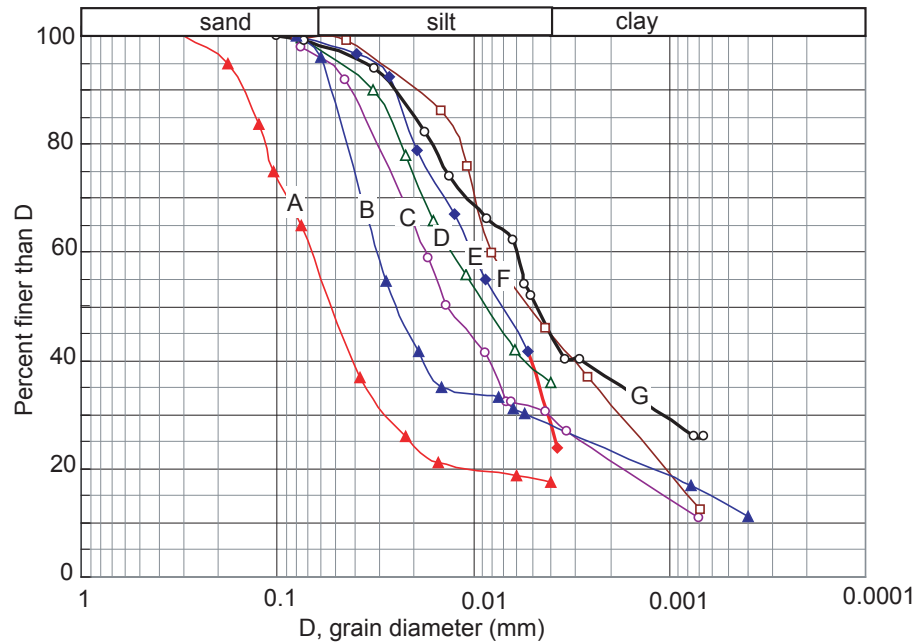
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**Fig. 14.** Sediment grain size analysis for sample locations shown by points A, B, C, D, G, and F in Fig. 11. Analysis by standard hydrometer and wet-sieving methods.

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